

Supernova/Acceleration Probe (SNAP)

Mission Summary: Supernova studies led to the astonishing discovery of cosmic acceleration from the cosmological distance-redshift relation in 1998. This new mission, the Supernova/Acceleration Probe (SNAP), follows up with a detailed investigation of the nature of the dark energy responsible for the acceleration, with direct impact on fundamental theories of physics, cosmology, and gravitation.

SNAP will study thousands of high redshift supernovae, each with unprecedented precision, using a 2-meter telescope in space with a one degree wide field-of-view and a unique billion-pixel camera (see Figure 1 and <http://snap.lbl.gov>). The SNAP instruments will cover the wavelength range from 400 nm to 1700 nm with imaging and spectrophotometry, and can discover and study supernovae from redshifts $z=0.3-1.7$ with equal accuracy. The supernovae will be used as cosmic markers of the scale of the universe over time to construct a history of the universe's growth. Copious complementary cosmological and astrophysical information will be produced from the resulting wide, deep images; in particular, weak gravitational lensing will be an important part of the science mission.

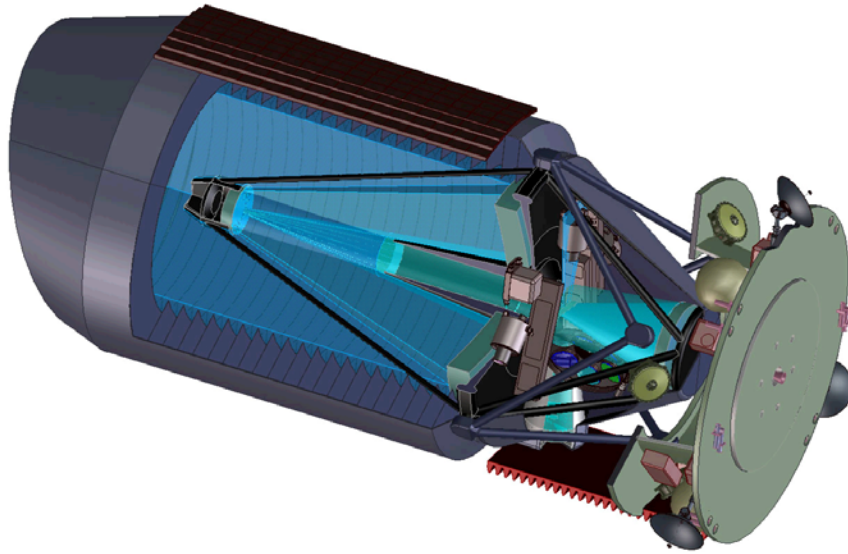


Figure 1: Cutaway view of the SNAP satellite: the secondary mirror is shown at left while the spacecraft bus and instruments are to the right.

Dark Energy – A Critical Clue: Observations that distant supernovae were dimmer than expected from a matter dominated distance-redshift relation, first presented in January 1998, provided the first direct experimental evidence for an accelerating universe. Originally interpreted as a positive value of Einstein's cosmological constant, this can also be attributed to a new unknown energy (termed “dark energy”) that permeates all of space. In the four years since, these results have been reinforced by the recent measurements of the cosmic microwave background (CMB) anisotropy power spectrum, especially when taken together with measurements of the mass density of the universe.

The Roadmap for the SEU theme embraces several fundamental scientific quests that

SNAP directly addresses: Dark energy holds the key both to forecasting our cosmic destiny and exploring the ultimate limits of gravity and energy in the universe. It currently forces the expansion of the universe into an accelerating phase which has crucial implications for its dynamical fate, the heat death and light horizon catastrophes, and even the validity of fundamental physics theories such as string theory. Measurement of the equation of state today, or at low redshifts, will not answer the question of our destiny – will the universe expand forever, ever more rapidly and cooling into stillness, as our light horizon closes in? – without additional information on the time variation of the underlying physical process, which SNAP can provide. Likewise it can address: is the dark energy “merely” a cosmological constant, or quintessence with a constant equation of state, or a richer dynamical scalar field? Dark energy could well also hold critical clues to the nature of gravity, opening a window on deviations from general relativity in the form of higher dimension or scalar-tensor theories.

The promise of SNAP and the central importance of elucidating the mystery of dark energy has been examined and confirmed by extensive peer and community review, including SAGENAP and HEPAP panels. These cosmic frontiers are a central part of the OSS strategic plan and the Structure and Evolution of the Universe theme – after all, dark energy composes 70% of the universe and holds the key to our cosmic fate.

Connecting Quarks with the Cosmos: Eleven Science ‘Questions for the New Century’, Phase I of the NRC study on the Physics of the Universe, notes “Deciphering the nature of dark matter and dark energy is one of the most important goals in the physics of the universe. The solutions to these problems will cast light not only on the fate of the universe but the very nature of matter, space, and time.”

Science Reach: SNAP will answer this fundamental challenge by constructing a supernova Hubble diagram that will achieve a new level of control over systematic uncertainties, addressing all of the known and proposed sources of possible error. This would be a landmark fundamental measurement, a clear history of the expansion rate over the past 10 billion years. Such a measurement using several thousand supernovae would provide precision determination of the major cosmological parameters: Ω_M to ± 0.02 and both Ω_Λ and the universe's curvature Ω_k to ± 0.05 , as well as dark energy properties (see Figure 2).

The goal is first to provide a secure measurement of Ω_M and Ω_Λ that would complement planned precision measurements from the CMB and astronomical studies (note that they would be largely orthogonal in the $\Omega_M - \Omega_\Lambda$ plane). The measurement of curvature itself would test the standard cosmological model, by comparing a measurement at redshift $z \approx 1$ to the CMB curvature measurement at $z \approx 1000$.

SNAP's science reach then explores the nature of the dark energy, a fundamentally new entity pervading – and dominating – the universe, even more exotic than dark matter itself. The simplest measurement here will be the effective pressure to density ratio, $w = p/\rho$, which SNAP can measure to ± 0.05 for a constant- w scenario. However, the practically unconstrained range of dark energy models includes many theories, which can only be differentiated by studying their effect on the universe's expansion over a wide

range of redshifts. This is where SNAP's tight control of systematics and statistical uncertainty at each redshift bin from 0.3 to 1.7 is crucial. Changes in p/p (notated w' and a definitive distinction from a cosmological constant model) will be measurable to ± 0.15 , given independent constraints on Ω_M at the ± 0.04 level. Moreover, the shape of the Hubble diagram, its record of the universe's growth spurts and slowdowns, can differentiate classes of dark energy models – and might make it possible to characterize the potential-energy curve of the dark-energy scalar field, pointing us to the underlying physics. The science reach for studying cosmological parameters using Type Ia supernovae to $z=1.7$ is shown in Figure 2.

Assuming:	Ω_M		Ω_Λ or $\Omega_{d.e.}$			
	stat	sys	stat	sys		
$w = -1$	0.02	0.02	0.05	<0.01		
$w = -1, \text{ flat}$			0.01	0.02	w stat sys	
$w = \text{const.}, \text{ flat}$			0.02	0.02	0.05	<0.01
$\Omega_M, \Omega_k \text{ known}$ $w = \text{const.}$					0.02	<0.01
$\Omega_M, \Omega_k \text{ known}$ $w(z) = w + w'z$					0.08	<0.01
					0.12	0.15

Figure 2: SNAP's science reach follows from a well measured sample of 2000 Type Ia supernovae distributed over a redshift range $z=0.3-1.7$. SNAP is uniquely able to measure the equation of state w precisely and detect its time variation $w'=dw/dz$.

Supernova Systematics – Accuracy and Precision: As a space experiment SNAP will be able to study supernovae over a much larger range of redshifts than has been possible with the current ground-based measurements – over a wide wavelength range unhindered by the Earth's atmosphere and with much higher precision and accuracy. Many of these systematics-bounding measurements are only achievable in a space environment with low “sky” noise and a very small point spread function (critical for lensing as well). Unlike other cosmological probes supernova studies have progressed to the point that a detailed catalog of known and possible systematic uncertainties has been compiled – and, more importantly, approaches have been developed to constrain each one.

For example, an approach to the problem of possible supernova evolution uses the rich stream of information that the expanding supernova atmospheres send us in the form of their spectral time series. A series of measurements will be constructed for each supernova that define systematics-bounding subsets of the Type Ia category. These data (e.g., supernova risetime, early detection to eliminate Malmquist bias, lightcurve peak-to-

tail ratio, identification of the Type Ia-defining Si II spectral feature, separation of supernova light from host galaxy light, and identification of host galaxy morphology, etc.) make it possible to study each individual supernova and measure enough of its physical properties to recognize deviations from standard brightness subtypes. Only the *change* in brightness as a function of the parameters classifying a subtype is needed, not any intrinsic brightness. (Supernovae cannot change their brightness in one measured wavelength range without affecting brightness somewhere else in the spectral time series – an effect that is well-captured by expanding atmosphere computer models.) By matching like to like among the supernova subtypes, we can construct independent Hubble diagrams for each, which when compared test systematic uncertainties at the targeted level.

While the thorough study of Type Ia supernovae drives the design of SNAP, the resulting instrument will have broad capabilities that will be desirable for complementary measurements, such as the study of dark matter through weak lensing techniques. Weak gravitational lensing can provide a map of the distribution of the dark matter in the universe, and with photometric redshifts weak lensing will permit studies of the evolution of structure as a function of redshift. The exquisite image quality and stable point spread function from space dramatically reduce systematic uncertainties. Perhaps most importantly, weak lensing can measure Ω_M with uncertainties as low as ± 0.01 - 0.02 . This measurement will have little dependence on w , and such a constraint will play a crucial role in the supernova exploration of w' . Additional science comes from a known technique for calibrating Type II supernovae magnitudes, providing a supporting, and independent, Hubble diagram. Finally, SNAP's expected dataset will survey an area of sky over ten thousand times larger than the Hubble Deep Field, and two magnitudes deeper. The rich range of science that will result from these and SNAP Guest Survey programs can only be listed briefly in the last section of this short document.

We believe that the supernova-based measurement is unique in its state of readiness and its sensitivity to the nature of the universe's dark energy. SNAP provides a comprehensive mission that uses this approach to address both this most fundamental science and much more.

Addressing national science priorities: Five relevant national panel survey reports, from the National Academy of Sciences and the High Energy Physics Advisory Panel, recently set planning priorities for the fields of astronomy, fundamental particle physics, and for their intersection. The discovery of cosmic acceleration and dark energy may be unique in being addressed prominently by all of them.

(1) *NAS Astronomy and Astrophysics Decadal Survey* – commissioned by NASA and NSF: The Decadal Survey called dark energy “one of the most exciting developments of the past decade” and identified the science addressed by SNAP as one of their highest priorities: “Confirmation that dark energy exists would be a physical discovery of the most fundamental significance.” SNAP was not yet a formulated mission at the time of the Decadal Survey, and thus was not explicitly considered as a named option, however SNAP is quite relevant to their recommendation of a wide-field telescope.

(2) *NAS Committee on Physics of the Universe* – commissioned by NASA, DOE, and NSF: As mentioned above, in their Phase I report they identified the study of dark energy as one of their key questions for the physics/astrophysics intersection: “Deciphering the nature of dark matter and dark energy is one of the most important goals in the physics of the universe. The solutions to these problems will cast light not only on the fate of the universe but the very nature of matter, space, and time.” Their pending Phase II report will consider proposed projects.

(3) *NAS Physics Survey Overview* – commissioned by NASA, NSF, and DOE: One of the six Grand Challenges listed is to determine the nature of dark matter and dark energy. They state, “Exciting questions are being addressed: Is the expansion of the universe today accelerating as a result of some mysterious form of energy?”

(4) *NAS Committee on Gravitational Physics* – commissioned by NASA, NSF, and DOE: One of their recommendations is to “use astronomical observations of supernovae and gravitational lensing to infer the distribution of dark matter and to measure the cosmological constant.”

(5) *High Energy Physics Advisory Panel (HEPAP) 20 year planning report* – a joint NSF-DOE committee: This report, representing the entire particle physics community, states that the study of the dark energy is at the heart of their field: “The quest to understand the origins of dark energy and dark matter are important components...Cosmological measurements of dark energy and particle dark matter have direct implications for particle physics.” The HEPAP panel goes on to strongly recommend funding the study phase of SNAP, including it in their project timeline.

A recent review of the SNAP project, commissioned by DOE, states, “SNAP will...provide the first precision cosmology measurements by directly addressing the nature of the dark energy... SNAP will have a unique ability to measure the variation in w [the dark energy equation of state] with redshift.”

The SNAP project comprises developments on three state of the art platforms: fundamental science, advanced technology, and future frontiers. By following the DOE Office of Science mission statement: “Explore the evolution and fate of the universe through the fundamental interactions of energy, matter, time and space”, SNAP also addresses a central question of the Cosmic Journeys Initiative with deep national implications: “Can we discover new physics?”

Technological advances from the project have direct applications to specific NASA themes as well as broad national priorities; for example, development of radiation hard CCDs and calibration systems for accurate photometric measurements will enable advances in general detector and remote sensing technology. For a more visionary prospect, just as researchers discovering X-rays and electrons in the last years of the 19th century could not guess the technological implications, it may be that the discovery of dark energy at the end of the 20th century holds unfathomed practical riches from gravity and fundamental physics.

Fitting into the NASA strategic plan and timeline: The SNAP mission builds upon one of the most important discoveries of the HST in studying the acceleration of the universe using supernovae. The SNAP project has been designed specifically to pick up where the HST leaves off in this field, and in the complementary field of weak lensing. The wide-field imager on SNAP is also the natural scientific follow-on to the Hubble Deep Field work, since its baseline projects will provide the same scientific community with data covering 13000 times the area of the HDF to approximately the same depth per exposure; coadded magnitudes will reach $m_{AB}=31.6$. Combining high accuracy multiband photometry with a deep, wide field will revolutionize many astrophysical studies.

The current OSS strategic plan puts the NGST as one of the highest priorities. Since the NGST is intended to go significantly deeper than HST, but not much wider, the natural complementary space telescope would be a wide field design such as SNAP. SNAP is a natural “feeder” – a survey telescope used to select targets for the NGST, as well as a powerful scientific instrument in its own right.

NASA missions such as MAP will expand the era of precision cosmology. But while MAP provides invaluable information on the curvature of the spatial geometry and the dark energy density, it is not sensitive to the form of the dark energy – its equation of state w . SNAP acts in a marvelously synergistic fashion, with the two missions together increasing precision far beyond the abilities of either alone. Even Planck by itself can only limit the equation of state w to within 0.25 (1σ), less restrictive than current supernovae plus CMB experiments. Another advantage SNAP provides is in the time domain. Gamma ray burst afterglows, microlensing and strong lensing events, AGNs, variable and fast moving objects – the active, violent universe – will all be uncovered by SNAP. We can hope to detect events we have not yet imagined.

The SNAP timeline would put it after the next series of wide-field projects on the ground, including the CFHT Legacy Survey with MegaCam and likely the VISTA telescope. The SNAP project has been designed specifically to pick up where these hit systematic uncertainty limits imposed by the nature of ground based observing. Its research programs include a variety of crucial cosmic questions, pushing beyond ground data in both degree and kind (e.g. greater precision and new parameters such as variation w' of the dark energy equation of state).

SNAP builds on the momentum of the recent exciting discoveries to probe essential unknowns that now stymie the advance of fundamental physics and astrophysics understanding. The recent DOE HEPAP planning report gives a timeline for the implementation of SNAP that takes advantage of the readiness of current science and technology; the SNAP mission is in an enviable position of just bringing state of the art technology to fruition. Its radiation hard CCDs and large stable detector mosaics are already being tested and deployed at major national observatories and facilities. LBL CCDs are in use at Kitt Peak National Observatory (see Figure 3) and the wavelength limited HgCdTe infrared detectors to be used are an integral part of Hubble’s Wide Field Camera 3. SNAP would be the first space application of the well tested innovative radiation hard CCDs: no novel space hardware is needed, just the natural growth of developed technology, so no funding is sought for new technology. This state of readiness puts the mission on a near term timeline.

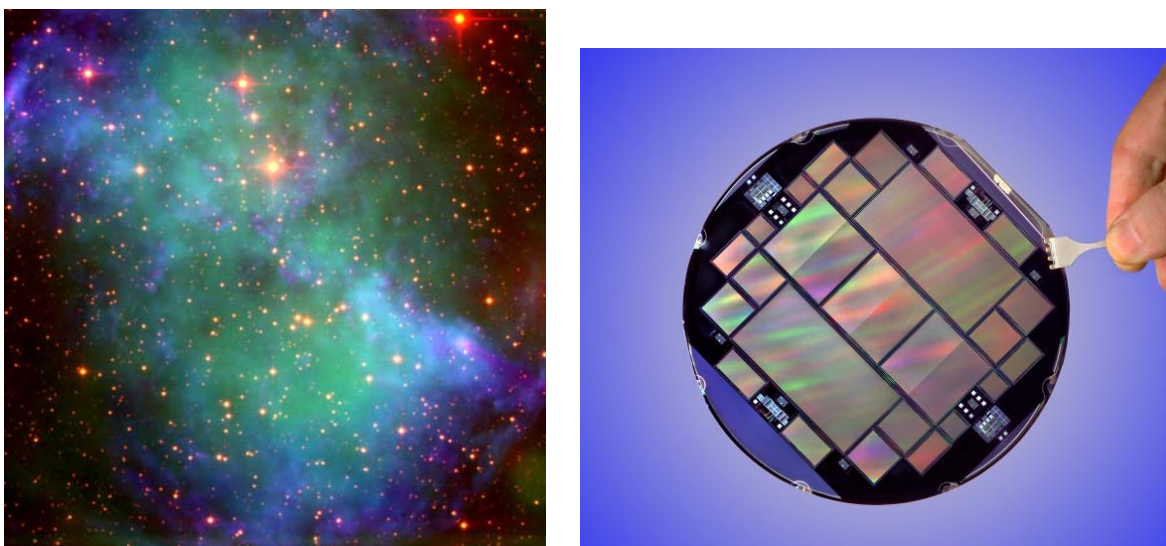


Figure 3: A new SNAP technology LBNL 2048x2048 back-illuminated fully-depleted p-channel CCD caught the image at left of the Dumbell Nebula (NGC 6853) with the WIYN 3.5 meter telescope at the Kitt Peak National Observatory (courtesy NOAO; see the September 2001 NOAO newsletter cover at <http://www.noao.edu>). The one-micron filter image was assembled from images taken through narrow-band filters centered roughly on the $H\alpha$ (blue) and the [SIII] 9532Å emission lines (green), and an intermediate-band filter centered at 1.02 microns that includes emission from HeII at 10124Å (red). At right is a high-resistivity p-channel CCD 6" wafer. The three 9 megapixel CCDs across the middle are based on a concept for SNAP.

Partnerships and Guest Surveys: Strong international interest in collaborating on SNAP exists. Scientists from France and Sweden actively participate and there have been requests from other countries. Formal national agency participation from these countries is also being aggressively pursued by these scientists. The SNAP collaboration already includes some 12 academic institutions, and new university groups are joining every few months. Beyond this collaboration, the resulting data archives will be used by scientists around the world, while the instrumentation is expected to become more and more available for Guest Survey programs as the primary missions ramp down over the first few years. The resources are invaluable: detailed studies of thousands of Type Ia and II supernovae, a wide field survey of 20 square degrees down to $m_{AB} = 31.6$, and extremely wide fields for weak lensing (including large area maps of the total mass distribution) and a host of other science down to 28.5 mag in UBVRI over 3000 square degrees.

The plethora of science generated covers myriad topics such as stellar populations, galactic structure, and clustering correlation functions, weak and strong gravitational lensing, evolution of large-scale structure, transient and rare objects, and solar system studies. In fact, just at the January 2002 American Astronomical Society meeting community researchers presented 18 talks and 6 posters in a special grouping dedicated to the broad range of science with SNAP (for a comprehensive listing please see <http://snap.lbl.gov/pubdocs/aastalks.html>).

In addition to this strong community support, the mission will require and benefit from close partnership between NASA and DOE. NASA has already been involved through its analysis of SNAP at the IMDC (Integrated Mission Design Center) and the ISAL (Instrument Synthesis Analysis Lab). Industrial partners and aerospace vendors will play an important role in the technology transfer, development, and manufacture. These studies provide confidence that there are no technological obstacles and that costs and requirements are well in hand, enabling a clear path to exciting advances in fundamental and wide ranging science.

For further information see <http://snap.lbl.gov> and the community *Resource Book on Dark Energy* at <http://supernova.lbl.gov/~evlinder/sci.html>